

# Measurements of high $p_T$ identified particles $v_2$ and $v_4$ in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions by PHENIX

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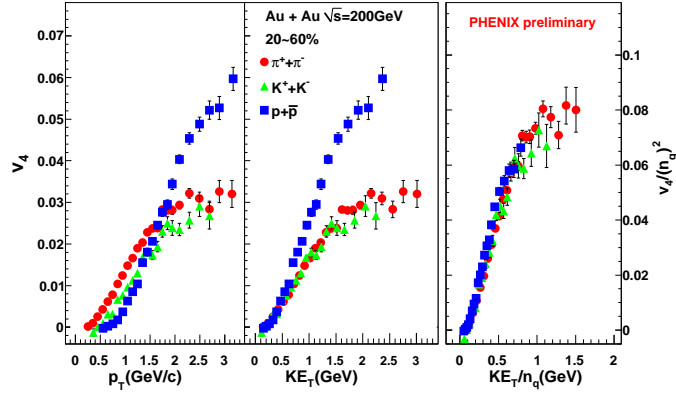
**Abstract.** The  $v_2$  and  $v_4$  of pions, kaons and protons have been measured by PHENIX in 200 GeV Au+Au collisions up to  $p_T \sim 6$  GeV/c and 4 GeV/c, respectively. The  $v_4$  of all these identified particles have been found to scale with the number of constituent quarks and all these particles have a similar  $v_4/v_2^2$  ratio which is close to 0.9. The scaling behavior of  $v_2$  is studied at high  $p_T$  and a deviation from the universal scaling is observed for transverse kinetic energy ( $KE_T/n_q$ ) higher than 1 GeV.

## 1. Introduction

A hot, dense non-hadronic matter has been created at RHIC in ultra-relativistic heavy ion collision[1][2]. The anisotropic flow coefficients  $v_2$  and  $v_4$  provide sensitive information about the properties of the matter in the earliest stages of the heavy-ion collisions. The  $v_2$  of identified hadrons has been found to obey empirical scaling with the number of constituent quarks (NCQ) for  $KE_T$  and provides evidence that partonic degrees of freedom determine the early dynamics of the system[3]. In this work, the measurement of  $v_4$  will be used to further test this scaling. The  $v_4/v_2^2$  ratio has been proposed as a probe of ideal hydrodynamics and related to the degree of thermalization[4] in the system. Accurate measurements of identified particles  $v_4/v_2^2$  ratio will constrain the model calculations. The measurement of high  $p_T$  identified hadron  $v_2$  will allow us to test the limits of the NCQ scaling. If the anisotropic emission of particles in the high  $p_T$  region is dominated by parton energy loss, the NCQ scaling is expected to break since the energy loss mechanism affects all particle species similarly[5][6]. Determining the breaking point in the NCQ scaling will provide information on the limits of applicability of the hydrodynamic description of the system dynamics.

## 2. Analysis Method

During Run 7 of RHIC, the PHENIX experiment recorded 5.5 B minimum-bias 200 GeV Au + Au collision events and 2.2 B have been used for this work. Two new

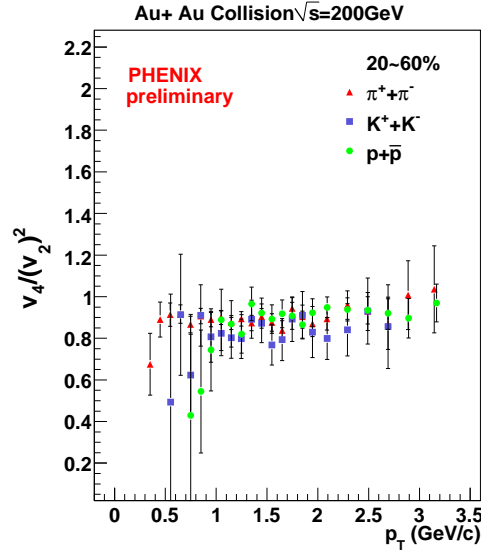


**Figure 1.** The  $v_4$  of pions, kaons and protons for 20 – 60% Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV

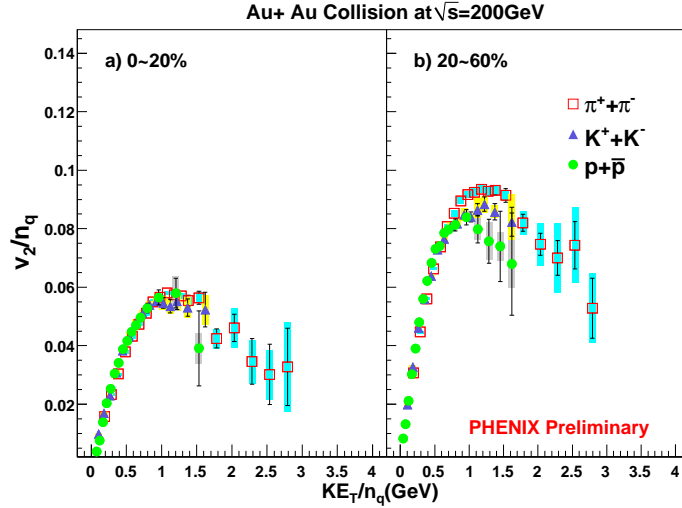
subsystem detectors were installed prior to Run 7, which significantly enhanced the PHENIX capabilities for identified particle anisotropic flow measurements. A time of flight detector (TOFW) was installed in the west arm of the PHENIX spectrometer. With  $\sigma_t = 75$  ps intrinsic timing resolution, the TOFW detector allows pion/kaon separation up to  $p_T \sim 2.8$  GeV/c, and kaon/proton separation up to  $p_T \sim 4.5$  GeV/c. Together with the previously installed Aerogel Cherenkov counter (ACC), the TOFW detector provides high  $p_T$  hadron identification in PHENIX. Combining the photon yield measured in the ACC and the mass-squared from TOFW, the kaon identification is extended to  $p_T \sim 4$  GeV/c, while the pion and proton identification reaches  $p_T \sim 7$  GeV/c. PHENIX was also upgraded with a new reaction plane detector (RxNP) which covers the rapidity region  $1.0 < |\eta| < 2.8$  with best resolution around 74% for  $v_2$  measurements. Since the RxNP is installed away from mid-rapidity, the non-flow effects from jet correlation are relatively small.

### 3. Results

Figure 1 shows the  $v_4$  of pions, kaons and protons in the 20 – 60% centrality bin in 200 GeV Au+Au collisions. In the left plot, the  $v_4$  is shown as a function of  $p_T$ . A clear mass ordering is observed for pions, kaons and protons, which is consistent with hydrodynamics behavior which has been previously observed for the elliptic flow. In the middle plot, the  $v_4$  measurements are presented as a function of transverse kinetic energy  $KE_T = m_T - m_0$ . In this unit, the mass ordering disappears at low  $KE_T$  which is consistent with hydrodynamic predictions. For  $KE_T$  greater than about 0.5 GeV, kaons and pions show much less  $v_4$  than protons. A universal behavior for baryons and mesons is observed when  $KE_T$  is divided by the  $n_q$  (number of constituent quarks) and the  $v_4$  values are divided by the  $n_q^2$ . This universal behavior has also been observed in the measurements of  $v_2$  for identified hadrons[3]. The results presented here further strengthen the conclusion that partonic flow has been built up in the early stages of the



**Figure 2.** The  $v_4/v_2^2$  for pions, kaons and protons as a function of  $p_T$  in the 20 – 60% centrality class in  $\sqrt{s_{NN}} = 200$  GeV Au+Au collisions.



**Figure 3.** Constituent quark scaling of elliptic flow,  $v_2$  for pions, kaons and protons as a function of transverse kinetic energy per quark ( $KE_T$ ) measured in two centrality classes: (left) 0 – 20%, and (right) 20 – 60%.

heavy-ion collisions at RHIC.

Figure 2 shows the  $v_4/v_2^2$  ratio for pions, kaons and protons as a function of  $p_T$  in the 20 – 60% centrality bin. This ratio is flat with  $p_T$  in the measured range and is independent of the particle species within errors. We analyze the results in terms of a simple coalescence model:

$$\frac{v_{4,m}(2p_T)}{v_{2,m}^2(2p_T)} = \alpha \left( \frac{1}{4} + \frac{1}{2} \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)} \right) \quad (1a)$$

$$\frac{v_{4,b}(3p_T)}{v_{2,b}^2(3p_T)} = \alpha \left( \frac{1}{3} + \frac{1}{3} \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)} \right) \quad (1b)$$

where  $v_{4,m}(p_T)$ ,  $v_{4,b}(p_T)$  and  $v_{4,q}(p_T)$  represent the meson, baryon and quark  $v_4$  respectively, and  $v_{2,m}(p_T)$ ,  $v_{2,b}(p_T)$  and  $v_{2,q}(p_T)$  represent the meson, baryon and quark  $v_2$ . Using the measured  $v_4/v_2^2$  ratio around 0.9 for both baryons and mesons, from equations (1a) and (1b), we obtain that the parton  $v_{4,q}/v_{2,q}^2$  ratio is around 0.5 and the parameter  $\alpha$  is around 1.8. This result indicates that a thermalized partonic liquid has been produced at RHIC.

Using the high  $p_T$  elliptic flow results, we can study the limits of applicability of the hydrodynamic description. Figure 3 shows the  $v_2$  of pions, kaons and protons as a function of  $KE_T$  in two centrality bins. Both  $v_2$  and  $KE_T$  have been divided by the  $n_q$ . The left plot is the result in the 0 – 20% centrality bin, and the right plot is the result in the 20 – 60% centrality bin. In 20 – 60% collisions, the NCQ scaling begins to break as the  $KE_T/n_q$  exceeds  $\sim 1$  GeV. This indicates that the origin of the  $v_2$  is based in hydrodynamics collective flow and parton recombination in the low  $KE_T$  region, but above  $KE_T/n_q \sim 1$  GeV, the contribution from parton energy loss become increasingly important.

#### 4. Conclusions

The measurements of pion, kaon and proton  $v_2$  and  $v_4$  have been extended up to a  $p_T$  of 6 GeV/c and 4 GeV/c respectively by PHENIX. The NCQ scaling has been tested for  $v_4$  and been found to hold for  $KE_T/n_q$  up to 1 GeV, indicating that partonic flow governs the bulk dynamics in heavy-ion collisions at RHIC. The mesons and baryons have a similar ratio of  $v_4/v_2^2$ , which is consistent with expectations for a thermalized partonic system in which hadrons at the intermediate  $p_T$  region are produced by parton recombination. The  $v_2$  measurement shows that the NCQ scaling begins to break for  $KE_T/n_q$  above 1 GeV in the 20 – 60% centrality class, which suggests that hard-scattering may be the dominant production mechanism for both baryons and mesons in this  $KE_T/n_q$  range and thus parton energy loss effects play a significant role in generating the azimuthal anisotropy in particle emission.

#### 5. References

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